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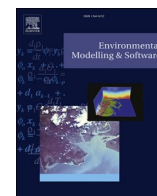
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Multi-criteria decision analysis in Bayesian networks - Diagnosing ecosystem service trade-offs in a hydropower regulated river

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ABSTRACT

The paper demonstrates the use of Bayesian networks in multicriteria decision analysis (MCDA) of environmental design alternatives for environmental flows (eflows) and physical habitat remediation measures in the Mandalselva River in Norway. We demonstrate how MCDA using multi-attribute value functions can be implemented in a Bayesian network with decision and utility nodes. An object-oriented Bayesian network is used to integrate impacts computed in quantitative sub-models of hydropower revenues and Atlantic salmon smolt production and qualitative judgement models of mesohabitat fishability and riverscape aesthetics. We show how conditional probability tables are useful for modelling uncertainty in value scaling functions, and variance in criteria weights due to different stakeholder preferences. While the paper demonstrates the technical feasibility of MCDA in a BN, we also discuss the challenges of providing decision-support to a real-world habitat remediation process.

1. Introduction

Environmental flow (eflow) has been defined as ‘the hydrological regime required to sustain freshwater and estuarine ecosystems, and the human livelihoods and well-being that depend on them’ (Acreman et al., 2014). Concessions to regulate rivers for hydropower production in Norway have historically evaluated eflow requirements and physical habitat mitigation measures separately. It is unusual to explicitly compare costs against environmental objectives in order to determine eflow, despite the assessment of ‘disproportionate cost’ being required by the Water Framework Directive (WFD) (Finstad et al., 2007). Recently, Norwegian authorities conducted a national screening project to prioritize the renewal of existing concessions where the most negative environmental impacts could be reduced at the lowest possible foregone power production (Sørensen et al., 2013). They prioritized concession renewals based on an evaluation of foregone hydropower revenue and the magnitude of environmental improvements on important fish

populations, biodiversity and landscape impacts and recreational use. One of the shortcomings of the study was not evaluating the potential for physical habitat restoration measures to partly substitute for stricter environmental flow requirements that follow from the application of the WFD in the revision process. Not considering the synergistic interactions between environmental compensation measures means that the costs of achieving good ecological potential under the WFD are likely to be overestimated (Barton et al., 2016b). More broadly, habitat restoration on-site, combined with offsetting measures can offer net gains to biodiversity (BBOP, 2009), as well as to other user interests such as recreation (Aas and Onstad, 2013). The central handbook on environmental design in regulated salmon rivers in Norway (Forseth and Harby, 2014) outlines steps for water negotiations as input to action plans for rivers, but proposes no formal method for assessing trade-offs across management objectives. In this study we propose such a formalized multi-criteria decision analysis (MCDA) to evaluating the trade-offs between hydropower production and cultural ecosystem services of

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recreational salmon fishing and riparian landscape aesthetics; and the supporting service of habitat quality for salmon smolt. We demonstrate how different quantitative and qualitative impact assessments can be combined in an Object-Oriented Bayesian Network (OOBN) with nodes for valuation functions, criteria weights and decision nodes, in order to consistently integrate uncertainty from different impact model domains within MCDA. The model is deployed in an online interface to ease communication with a wider community. To our knowledge this is the first example in Norway of MCDA integrating assessment of eflows and physical habitat restoration measures through the application of a Bayesian network approach.

1.1. Environmental design in hydropower river regulation

Research linking the economics of hydropower operation and physical river restoration measures to environmental outcomes has been limited due to the computational complexities of linking biophysical and economic models of varying resolution and data sources (Barton et al., 2010; Charmasson and Zinke, 2011; Niu and Insley, 2013; Person et al., 2014; Bustos et al., 2017). Jager and Smith (2008) found that earlier studies have optimized hydropower production against simple fish habitat objectives, or ignored hydropower objectives altogether in optimizing hydraulic and fish stocking objectives. Forseth and Harby (2014) propose an environmental design approach to regulated salmon rivers that brings together the state of knowledge on flow requirements of hydropower, environmental flows and morphological river restoration measures. Their Handbook proposes that trade-off appraisals be made through 'water negotiations' based on appraisal of multiple environmental design objectives. Recently, Bustos et al. (2017) demonstrated cost-effectiveness comparing hydropower production economics and salmon habitat restoration costs against productivity of Atlantic salmon. They integrated a series of models including hydropower production, river hydraulics, channel wetted area and salmon smolt productivity. While their study used historical hydrological data, the cost-effectiveness of alternatives was assessed in terms of mean smolt production per Norwegian kroner (NOK) in foregone power and remediation costs. In the present study we extend the Bustos et al. (2017) cost-effectiveness analysis to include recreational fishing and river aesthetics. We assess whether the conclusions from their cost-effectiveness analysis are modified by taking a multi-criteria decision approach that includes cultural ecosystem services which may have non-linear relationships to eflows.

1.2. Modelling uncertainty in environmental flows design

Acreman et al. (2014) reviewed the changing role of ecohydrological science in guiding eflows, the hydrological regime required to sustain freshwater and estuarine ecosystems and the livelihoods and well-being that depend on them. Recent advances include modelling of dynamics in hydrological analysis of flow regimes and addressing more than one stressor (flow, channel morphology). Because all methods and data have a degree of uncertainty, Acreman and colleagues stress the importance of risk communication between scientists, practitioners, policy-makers and the public. The present study contributes to the broader literature on modelling river restoration in the context of environmental flows and approaches to explicit calculation of uncertainty in decision-support models.

The present study builds on prior experiences in using Bayesian Networks (BNs) to model river management decisions. For example, Uusitalo et al. (2005) estimated Atlantic salmon smolt carrying capacity of rivers using expert knowledge in a BN in HUGIN software, identifying large disagreement in experts' judgement. They conclude that operational management objectives other than those based on maximal smolt production levels should be considered in order to decrease the uncertainty connected with evaluation of management success. Chan et al. (2012) used Bayesian network models in Netica software to model

relationships between dry season flows in an Australian river affected by agricultural irrigation, and key aspects of biology of barramundi and sooty grunter fish species. BNs were largely based on expert knowledge due to the lack of quantified biological knowledge, but could later be verification against field observations. Sometimes also called conditional probability networks, BNs have been used to formalize expert ecological knowledge of hydrological regimes on fish habitat (Shenton et al., 2011; Horne et al., 2018). Similarly, Gawne et al. (2012) demonstrated the use of a BN as a decision support tool for water supply and quality of wetlands in Australia to maximize outcomes on population health of four native fish. Shenton et al. (2014) integrated dynamic simulations from a hydrological sub-model with an established expert-based ecological model of grayling fish habitat spawning, larvae transport and recruitment. In the present study we contribute to this literature by demonstrating a combined impact modelling of morphological measures and eflow.

Marsili-Libelli et al. (2013) implement an instream flow assessment method modelling uncertain habitat suitability in large scale river modelling in Tuscany, Italy. They use fuzzy logic to implement uncertainty in expert judgement about habitat suitability curves under variable hydrological conditions. In the present study we show how uncertainty and non-linearity in expert assessment of habitat suitability curves can be implemented in conditional probability tables.

1.3. Multi-criteria decision analysis in a Bayesian setting

Landis et al. (2017) argue that Bayesian networks could also be used as the computational background for MCDA of risk-based adaptive environmental management. Bayesian networks has been used in multi-criteria decision analyses (MCDA) to support decisions in different fields, in the transport and safety field (Fenton and Neil, 2001), decommissioning of offshore oil and gas platforms (Henrion et al., 2015), urban planning (Langemeyer et al., 2020), in the diagnosis of significant adverse effect of the EU Water Framework Directive on hydropower production in Norway (Barton et al., 2016b), and in the evaluation of which nutrient abatement measure optimally improves the condition of a coastal ecosystem (Lehikoinen et al., 2014).

Huang et al. (2011) conducted a review of environmental applications of MCDA in the period 2000 to 2009. Vassoney et al. (2017) analyzed all peer-reviewed articles on the use of multicriteria analysis for sustainable hydropower planning and management from 2000 to 2015. In either review no papers were cited that used Bayesian network applications of MCDA to environmental management of freshwater ecosystems. However, there is literature that supports the use of Bayesian Network as MCDA tool in this field.

Varis (1997) documented and discussed the use of influence diagrams and belief networks, and their relation to decision trees. The examples provided were focused on environmental and resource management of freshwater and fisheries studies. In addition, Varis and Kuikka (1997) showed the appropriateness of Bayesian networks for handling problems in environmental and resource management such as to assess and safeguard the wild salmon stocks in the Baltic Sea under the pressure of extensive commercial fishery of reared salmon. They showed that Bayesian networks enhance the communication among experts using analytically based arguments, allowed to find inconsistencies in information, and to calculate joint predictions supporting decision making based on more balanced information.

In recent years, the use of Bayesian network for MCDA has increased for the field of environmental management in freshwater systems. Bayesian networks has been applied by Stewart-Koster et al. (2010) to support the prioritization of flow and catchment restoration alternatives, including the cost-effectiveness of the interventions. Holmes et al. (2018) used Bayesian Networks as a support tool for stream fisheries management with the objective of diagnose the factors limiting stream trout fisheries. Related to impacts on fish migrations from the hydropower structure and operations in the Northern Hemisphere a Bayesian

network was used to combine and show the effectiveness of possible fishpass structures, and the mortality rate from the hydropower turbines (Wilkes et al., 2018).

Reichert et al. (2015) discuss requirements for environmental decision support, arguing that a combination of probability theory and scenario planning with multi-attribute utility theory fulfills requirements for representation and quantification of scientific knowledge, elicitation of societal preferences and communication with authorities, politicians and the public. They argue for explicit modelling of ecological state, as separate from other ecosystem services, in order to better account for complexity in valuation. They present a multi-criteria decision-making process in which uncertainty is considered explicitly in multi-attribute valuation functions. Beinat (1997) demonstrated how to model uncertainty in marginal value functions in multi-attribute utility models for MCDA. In the present study we show how uncertainty in value functions can be implemented using conditional probability tables.

Reichert et al. (2015) conclude that more research is needed on value aggregation in environmental decision support, and in particular, non-additive approaches that consider joint fulfillment of management goals. MCDA has been used extensively in evaluating river regulation in Finland, testing a variety of additive and non-additive value elicitation techniques, discovering differences in weighting of river restoration criteria across multiple stakeholders (Marttunen and Suomalainen, 2005; Marttunen and Hamalainen, 2008; Marttunen et al., 2008). Variation in stakeholder weighting of criteria is addressed through sensitivity analysis. Convertino et al. (2013) demonstrated non-linear MCDA aggregation in sustainable river restoration alternatives using their model ProMAA, which can use probability distributions of criteria utilities and weight coefficients for assessing probabilities of “likely rank events” based on pairwise comparison of alternatives in an integrated scale. They demonstrated probability distribution of weights by assigning an arbitrary, fixed standard deviation to all criteria weights instead of point values. In the present study we demonstrate a criteria weight probability distribution generated by variation in stakeholder perspectives.

Convertino et al. (2013) emphasised the information costs involved in obtaining expert judgements of value in MCDA with many criteria weight combinations. Considering information costs and value, researchers have advised caution in modelling uncertainty without evaluating the decision support of additional probabilistic information in otherwise deterministic models. Uusitalo et al. (2015) recommends using information value analysis to evaluate increasing model complexity. Linkov et al. (2015) also argue for a weight-of-evidence approach to quantitative data integration in multi-criteria decision analysis, specifically advocating Bayesian methods for value-of-information analysis.

In the present study we discuss the scope for conducting value of information analysis in object-oriented Bayesian networks (OOBN). OOBN make it possible to subdivide a network into submodels that can be independently specified by domain experts, facilitating analysis and communication of complex nested model structure (Barton et al., 2012).

The paper is laid out as follows. In section 2 (materials and methods) we present the MCDA framework combining the chain of models employed by Bustos et al. (2017) to assess costs and smolt productivity. We extend the impact assessment to the cultural ecosystem services of river aesthetics and angling experience. We present how we use OOBNs to implement multi-criteria decision analysis. Supplementary Material further documentation of sub-networks and assessments that were needed to generate them. An online demonstration version of the network is available at <http://demo.hugin.com/example/MCDA.OOBN>. In section 3 our results show how the features of Bayesian networks can be used to appraise environmental design decisions from different perspectives. Section 4 discusses the differences between our findings for preferred management alternatives based on MCDA and those of Bustos et al. (2017) based on cost-effectiveness analysis. We discuss the

advantages and limitations of our application of MCDA in an OOBN.

2. Materials and methods

In this section we first provide an introduction to the study area, the management problem and define the scenarios for eflows and habitat restoration that were modelled. We provide a summary of the chain of models employed by Bustos et al., (2017) to assess costs and smolt productivity. We explain how this work forms the basis for our extension of the impact assessment to the cultural ecosystem services of river aesthetics and fishing experience. Supporting Material provides additional details on sub-models. We then present the multi-criteria decision analysis framework and how we use a Bayesian network to implement it. Finally, we discuss the diagnostic tools we use to assess the model.

2.1. Study area

The Mandalselva River basin is located in southern Norway (58° N, 7° E). It originates in Setesdalsheiene at 600–800 m.a.s.l. The river is 115 km long and has a catchment area of 1800 km². It flows south to the town of Mandal where the majority of the people (13 000) inhabiting the catchment live. The remaining 5000 people live in rural areas of the catchment (L'Abée-Lund et al., 2009). The Mandalselva River varies from low to high gradients over short distances allowing a combination of fast currents, waterfalls, slow deep pools, wide and calm stretches and lakes. The Mandalselva was among the top 10 of Norway's most productive salmon rivers before the acidification period (appr. from 1920 to 2000) which eradicated the Atlantic salmon population in the river in the first part of the twentieth century (Hesthagen and Hansen, 1991). During this period several hydropower facilities were constructed including the lowest, Laudal hydropower plant, located within the river reach available to Atlantic salmon (the final migration barrier is located 47 km from the sea at the Kavfossen waterfall (Fig. 1)).

This power station involved a tunnel bypass of the bulk of the flow and produced a 5 km long minimum flow river stretch. Atlantic salmon production has been restored after liming and re-stocking (Hesthagen and Johnsen, 2004). In order to mitigate the aesthetic effects of the very low flow (originally 250 l/s) and maintain a continuous water surface in the Laudal minimum flow stretch, 11 stone weirs and one concrete weir were constructed in the 1980s. In this study we evaluate the potential effects of removing the stone weirs #3–5 and the Kleveland concrete weir #8 (Fig. 1), in order to improve salmon habitat and the river's suitability for salmon fishing (“fishability”) and aesthetics compared to costs of eflow and restorations measures.

2.2. Definition of management scenarios

The overall aim of the MCDA was to demonstrate how to model the optimal combinations of weir removal and discharge regimes measured by stakeholder preferences for hydropower production, smolt production, recreational fishability and river aesthetics. We aimed to test alternative scenarios including a proposal by the Norwegian Water Resources and Energy Directorate (NVE) for a trial minimum eflow regime which more than doubled the previous voluntary spill regime at Laudal in place since 1995. If salmon productivity could be improved by the trial eflow regime, the hydropower producer's 1995 concession would be open to revision by the authorities. The baseline scenario A represents the bypass flow prior to the introduction of NVE's trial minimum flow regime implemented in 2013. NVE's trial regime from 2013 was as follows (labelled scenario P4):

- During the spring salmon smolt migration period (set to last 14 days), approximately 50% of the inflow released in the river to avoid smolt turbine entrainment.

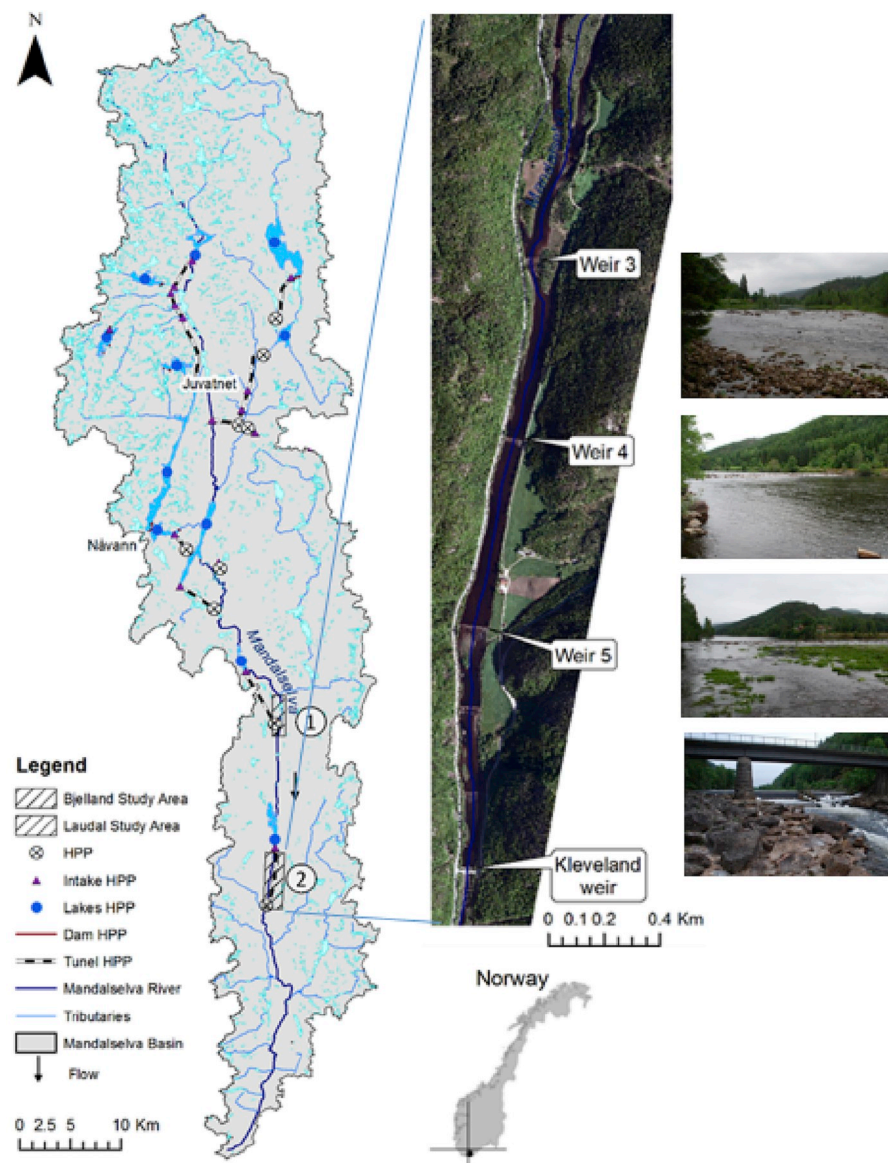


Fig. 1. Study area in the Mandal River, including four weirs considered in the study. Salmon migrate to and including location 1 in the figure. The focus of the analysis of measures in this study is the Laudal stretch location 2. Source: adapted from Bustos et al. (2017).

- During summer 8–25 m³/s are released, depending on inflow, to ensure both smolt production and upstream migration of adult salmon.
- During winter 6 m³/s are released to ensure salmon juvenile winter survival.

Scenario A is identical to Bustos et al., 2017, while the label “P” represents scenarios with photo-manipulated representation of river aesthetics under different flow conditions. Intermediate scenarios (P1 and P2) involved summer minimum flow releases at 3 and 4–6 m³/s, respectively.¹ Weir removal decreases wetted river surface area but typically increases river flow speed, thus potentially increasing salmon spawning area for any given flow rate (Fjeldstad et al., 2014). Increased flow speed can also increase recreational fishability in certain river segments while the impact on river aesthetics of decreased water surface area depends on recreational preferences (Pflueger et al., 2010).

¹ Scenario P3 was removed from the analysis because it lacked completely consistent photo-scenario information.

The habitat modification tested in this paper concerns removal of weirs and the addition of spawning gravel to the river reach. Weirs #3–5 and 8 in the Laudal residual flow reach were selected for further photo- and mesohabitat analysis because of their recreational accessibility and hence potential impact on river aesthetics and perceived fishability of the river. An overview of scenarios modelled in this paper is provided in Table 1 –where P denotes the photo-scenarios. Weir removal and addition of spawning gravel were modelled in all P1, P2, and P4 flow scenario combinations. A total of 16 (4 × 2 × 2) combinations of measures across all models are assessed in this paper (Table 1). Bustos et al. (2017) simulated a number of other intermediate scenarios with only marginal differences to P1, P2, P4 (see Supplementary Material S1).

Note: summer low flow rules were defined by a step function conditional on a range of inflows in P2 and P4. Aesthetic effects were evaluated at fixed flows 3.0, 6.0 and 15.0 m³/s. Intermediate scenario P3 was removed because it lacked a complete photo-scenario. In the rest of the paper flow scenarios are labelled “-Wp” if weirs are removed and “+G” if spawning gravel is added.

Table 1
Scenarios modelled in MCDA.

| Flow Scenario | Winter discharge (m ³ /s) | Spring discharge (% of inflow) | Summer discharge (m ³ /s) | Spring discharge (% of inflow) | Winter discharge (m ³ /s) | Weir removal (-Wp) | Spawning gravel addition to bypass section (+G) |
|---------------|--------------------------------------|--------------------------------|--------------------------------------|--------------------------------|--------------------------------------|--------------------|---|
| A | 1.0 | 0% | 3.0 | 0 | 1 | none/weirs | none/2000 m ² |
| P1 | 6.0 | 50% | 3.0 | 50 | 6 | #3–5 & 8 | |
| P2 | 6.0 | 50% | 4.0–6.0 (6) | 50 | 6 | | |
| P4 | 6.0 | 50% | 8.0–25.0 (15) | 50 | 6 | | |

2.3. Ecosystem service sub-models

The ecosystem service cascade framework links ecosystem structure to function, services, benefits and values (Haines-Young and Potschin, 2010). Later developments have emphasised the stepwise intervention of policy and management, adding feedback loops and stepwise updating (Spangenberg et al., 2014; Barton et al., 2017; Hausknot et al., 2017). Fig. 2 provides a conceptual overview of the cascade of ecosystem service models and the link to the MCDA as used in this paper. It shows how biophysical and economic submodels are integrated explicitly in the MCDA using object-oriented Bayesian network functionality. Limited stepwise feedback was part of our study through; (i) adjustment of environmental design scenarios modelled in Bustos et al. (2017) based on feedback from stakeholders to the outcomes for hydropower production, wetted area and smolt production; (ii) adjustment of impact weights based on updating of perspectives by hydropower company stakeholders; and (iii) scaling of impacts through consultation with domain experts.

An overview of the sub-models S1–S7 is presented below with further details available in the Supplementary Materials.

Hydropower energy foregone relative to the voluntary baseline scenario A was calculated using a power production potential function, considering turbine efficiency, net head of water and average water flow through the turbine. Annual foregone energy output was scaled with an average price for May 2012–May 2013 in order to be comparable to the study by Bustos et al. (2017). Fixed costs of weir removal and artificial establishment of spawning gravel were annualized and added to annual foregone revenues in each scenario, resulting in an incremental annual cost for each scenario relative to scenario A (see Supplementary Material

S1 for further documentation).

The flow regime in the bypass section discussed above determines the wetted area. Wetted area was determined using hydraulics calculations in HEC-RAS 1D (HEC-RAS, 2008), using a model developed by Fjeldstad et al. (2014). The hydraulic model estimates changes in wetted area, water velocity and water depth, which are subsequently inputs to mesohabitat quality classification and mapping. See Supplementary Material S2 for further documentation.

The effect of the hydrological regime on salmon production was determined using the individual-based salmon population model IB-salmon (Hedger et al., 2013a, Hedger et al., 2013, 2018). This model simulates salmon population abundances across salmon life-stages from juvenile (fry, parr, smolt) to adult (adult at sea, returning spawner) using functions that govern how individual salmon respond to the environment, such as temperature-dependent growth and density-dependent mortality. The model is 1-dimensionally spatially explicit, with the watercourse being compartmentalised into a series of sections, 50 m in length. Smolt production (the number of individuals migrating to sea) was used as the metric of population condition as a supporting ecosystem service. Smolt production is a commonly used metric because it represents the stage at which the population has experienced all sources of juvenile mortality in the river and is relatively easy to measure empirically. See Supplementary Material S3 for further documentation.

The hydraulic model HEC-RAS uses mapped river cross sections and flows to simulate spatial distribution of water velocities and water depths. We used these model data, combined with judgement of salmon fishers in the research team (pers.com. Fjeldstad), to classify physical conditions for fishing under different scenarios using the mesohabitat

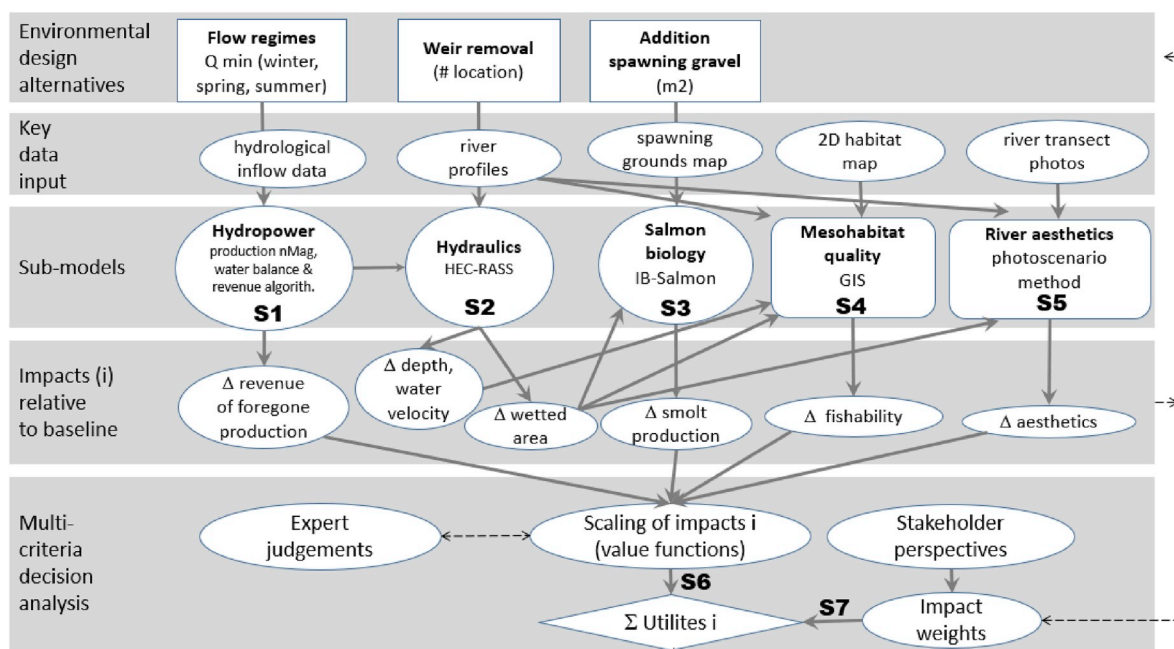


Fig. 2. Model overview. Cascade of ecosystem service models and link to multi-criteria decision analysis.

Note: Supplementary Materials S1–S7. Legend.

classification system by Borsanyi et al. (2004). Different mesohabitat types were plotted by experts in the bypass area, and one map was produced for each scenario and for each reach above weirs #3–5,8. Maps of the extent of each habitat type were generated for specific river summer discharges ($3 \text{ m}^3/\text{s}$, $6 \text{ m}^3/\text{s}$, $15 \text{ m}^3/\text{s}$), with and without weirs. We generated a matrix of changes in mesohabitat area relative to the baseline scenario A summer situation minimum flow of $3 \text{ m}^3/\text{s}$. Each mesohabitat class was then valued independently by 3 salmon fishers in the project team on a scale from 0 to 1 for their relative ‘fishability’. Mesohabitat mapping and expert scoring were combined in a sub-network embedded in the OOBN (Fig. 2). See [Supplementary Material S4](#) for further documentation of the sub-model.

Habitat remediation through weir removal affects riverscape aesthetics as wide and calm weir reservoir water surfaces are converted to a narrower, but more variable river. In fact, accessibility of river reaches - and hence potential aesthetic impacts - was the determining factor for which weirs were selected for scenario modelling in this study. We used photo-scenario and photo-simulation methods (Tress and Tress, 2003; Junker and Buchecker, 2008) to assess visual effects of combinations of different low flow regimes, with and without weir removal. Baseline photos at $6 \text{ m}^3/\text{s}$ were taken for river reaches around the selected weirs. Photoshop scenario illustrations were based on HEC-RAS 1D hydraulic modelling data for the parameters wetted area, water velocity and water depth (S2). Expert knowledge and systematic judgement were used to illustrate the specific water surface structures resulting from varying water velocities and water depths, including light and color of the water surface and shadows. Additionally, we used a 3 D visual modelling technique for the site with the largest weir structure at Kleveland bridge (pers. com. 3Dsmia/B. Dervo). This resulted in 3×4 photoscenarios which were evaluated by 6 experts familiar with the Laudal river reach for whether subjective aesthetics were ‘better’ or ‘worse’ than the situation actually observed with a discharge of $6 \text{ m}^3/\text{s}$. These responses were then rescaled relative to the reference scenario A in the MCDA. See [Supplementary Material S5](#) for further documentation of the sub-network.

2.4. MCDA using an object-oriented Bayesian Network (OOBN)

An OOBN is a hierarchical representation of a joint probability distribution over a set of random variables. It consists of a graphical structure describing dependence and independence relations between variables in the model represented as the nodes in the graph. The dependence relations are quantified using conditional probability

distributions. The hierarchical structure is created through the use of instance nodes which are realizations of self-contained sub networks within a network class. An instance node is connected to nodes in the encapsulating network class through its interface nodes. An OOBN can be augmented with decision and utility nodes and used to find decisions with optimal utility considering joint probabilities.

Fig. 3 shows the OOBN for the MCDA of environmental design in the Laudal River. The model structure shows the multi-attribute value theory (MAVT) approach to MCDA that was implemented, including - from top to bottom in the figure - design alternatives, design characteristics of the alternatives, impacts, scaling/valuation of impacts, and weighting of scaled impacts. Weighting of impacts is conditional on interests from different stakeholder perspectives.

Using OOBN as a meta-model to integrate different disciplinary sub-models (Koller and Pfeffer, 1997; Barton et al., 2016b) requires (i) converting model simulations into conditional probability tables in the main network, and (ii) linking the expert belief based sub-models to comparable assessment criteria. For MCDA-MAVT further steps include (iii) scaling/normalizing/valuing impacts so they can be compared, (iv) eliciting relative importance of impacts expressed as relative weights, and (v) comparing alternatives based on the summed weighted impacts. These are discussed in turn below.

(i) Learning conditional probabilities from model simulations.

Increase in smolt productivity and opportunity costs of foregone power in scenarios P1–P4 relative to scenario A were processed in STATA and then imported to Hugin Expert’s Learning Wizard. We used the Learning Wizard to discretize probability distributions of smolt and hydropower generation, then to generate conditional probability tables for all combinations of minimum flow and habitat restoration measures in Table 1. The Necessary Path Condition (NPC) algorithm (Hugin, 2014) was used to learn the conditional probability distributions of the smolt-hydropower impact combinations in the MCDA network (Fig. 3). Discretization of high resolution (near continuous) input data to interval distributions is necessary in order to combine these different data sets with discrete expert judgements on mesohabitat fishability and riverscape aesthetics (discussed below). Differences between scenario A and P1–4 were calculated in STATA - outside Hugin - to avoid information loss in discretizing probability distributions for input data coming from algorithms and models using high resolution data (daily time step). Probability distributions were

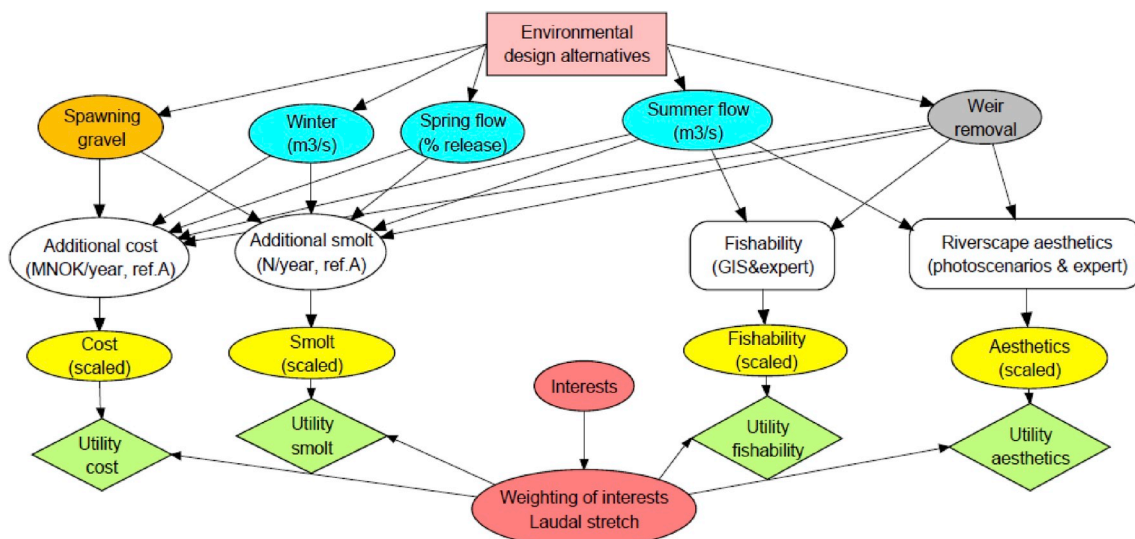


Fig. 3. Hugin Expert graphical user interface of the Bayesian network for the MCDA of environmental design in the Mandal River.

discretized as equal intervals in the likely impact range of each node to ease visual interpretation of differences between scenarios.

- (ii) **Integrating Bayesian belief sub-networks.** Sub-networks are linked to the main network through input-output nodes. Sub-networks for individual impacts can easily be updated without changes needing to be made to the upper level network (Johnson et al., 2013).
- (iii) **Scaling impacts.** The different units of impact for cost, smolt, fishability and aesthetics are scaled/normalized in separate nodes (yellow Fig. 3). Criteria weighting in MCDA using multi-attribute valuation theory is often linear and deterministic (Belton and Stewart, 2002). On the other hand, conditional probability tables in Bayesian networks allow for non-parametric, non-linear scaling/valuation of impacts. See Supplementary Material S6 for further documentation of the scaling of impacts on cost, smolt, fishability and aesthetics.
- (iv) **Eliciting preferences using relative weights.** Six stakeholder members of the reference group for Environmental Design in the Mandalselva River, volunteered to provide information on the relative importance of impacts in an anonymous questionnaire. While the six participating stakeholders did not represent all user groups, they represent a variety of institutions and user types, serving to demonstrate preference variation in an MCDA. Stakeholders granted permission to publish their preference weighting without reference to institutional affiliation, with the exception of Actor A who allowed the identification of hydropower interests (Fig. 4). Stakeholders were asked to distribute 100 points across the different criteria relative to their importance. In our Bayesian network application of MCDA we model these importance weights as probability distributions generated by variance in preferences across stakeholders. Fig. 5 shows how the relative importance of weights is represented by probability distributions conditional on different actor interests (anonymized for this paper). See Supplementary Material S7 for further details on stakeholder's relative weighting of impacts.

3. Results

We focus the presentation of results on how inference and diagnostic features of Bayesian belief network can be used to see the outcomes of MCDA with different types of evidence:

- default model without evidence (Fig. 6)
- actor interest evidence (Fig. 7)
- impact criteria weighting evidence (Fig. 8)

Fig. 6 illustrates the default model with no evidence inserted in which all decision alternatives are equally likely, indicated by equal

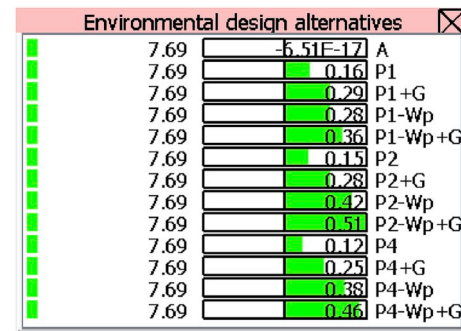


Fig. 5. Node monitor in Hugin Expert showing the utility of environmental design alternatives as green bars. Note: utilities are shown on the right hand side of the monitor. Probabilities on the left hand side indicate that all scenarios are being evaluated (equally likely). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

probabilities in the left hand side of the node monitor. Each node monitor shows the expected marginal utility of each state of that node variable in right hand side of the node monitor. (Inserting evidence in different parts of the model provides different diagnostic perspectives.

Once the network has been compiled, evidence in any part of the network can be assessed with no further computing time. We used HUGINs web deployment of probabilistic graphical models (Madsen et al., 2013) to deploy the model online where users can experiment with different scenarios and inferences: <http://demo.hugin.com/example/MCDA.OOBN>.

The decision node in Fig. 6 indicates the expected utility of each environmental design scenario (see also Fig. 5 for a zoomed in version). Scenario P2-Wp + G with 6 m³/s winter and summer flow, removal of weirs #3–5,8 and use of spawning gravel generates the highest expected utility of all scenarios, assuming all stakeholders have equal weight. Scenario P2-Wp + G has the highest expected utility when all actors' preferences have equal probability weight. Notably, streamflow measures alone – scenario P1, P2, P4 have roughly about half the utility of measures with habitat improvements including weir removal and spawning gravel. This 'total expected utility' perspective on the MCDA does not reflect the marginal contribution of individual design features.

Fig. 7 illustrates the use of Bayesian network in inference mode for diagnostic reasoning. It illustrates an actor interest perspective on the MCDA, in which a specific actor's perspective chosen as "evidence" (lower panel). With the chosen actor's preference weights (middle panel), the Bayesian network is used to infer utilities of the environmental design alternatives for that specific actor (upper panel). This is a unique model analysis feature of implementing MCDA in a BN.

Actor A (left hand panels) has a small negative expected utility

| Interests | Actor A ... | Actor B | Actor C | Actor D | Actor E | Actor F |
|-------------|-------------|---------|---------|---------|---------|---------|
| Cost | 0.53 | 0 | 0.1 | 0.05 | 0.2 | 0.2 |
| Smolt | 0.3 | 0.5 | 0.7 | 0.05 | 0.4 | 0.4 |
| Fishability | 0.1 | 0.3 | 0.1 | 0.05 | 0.2 | 0.3 |
| Aesthetics | 0.07 | 0.2 | 0.1 | 0.85 | 0.2 | 0.1 |

Fig. 4. Relative importance weights modelled as conditional probabilities. Shading in the Hugin conditional probability table represents relative probability.

- (v) **Calculation of utilities and comparison of alternatives.** The utility function used in Hugin Expert is an additive function of the weighted impact criteria compatible with MAVT (Beinat, 1997). Using the terminology of Bayesian Networks literature we model the MCDA as an 'influence diagram' (Kuikka et al., 1999; Kjaerulff and Madsen, 2007). Specifically, we use a decision node for environmental design alternatives and utility nodes to assess the utility of weighted impacts across alternatives. Once the network is compiled in Hugin Expert, node monitors provide the marginal utilities of every state in every node in the model. Fig. 5 provides an example of a node monitor for the decision node "environmental design alternatives". It shows the expected normalized utility of each alternative indicated on the right hand side. This is useful for the analyst to gain an overview of the relative importance of specific conditions/contexts for the utility of decision options. See Supplementary Material S7 for further details on how to model a weighted sum of utilities in an influence diagram in Hugin Expert.

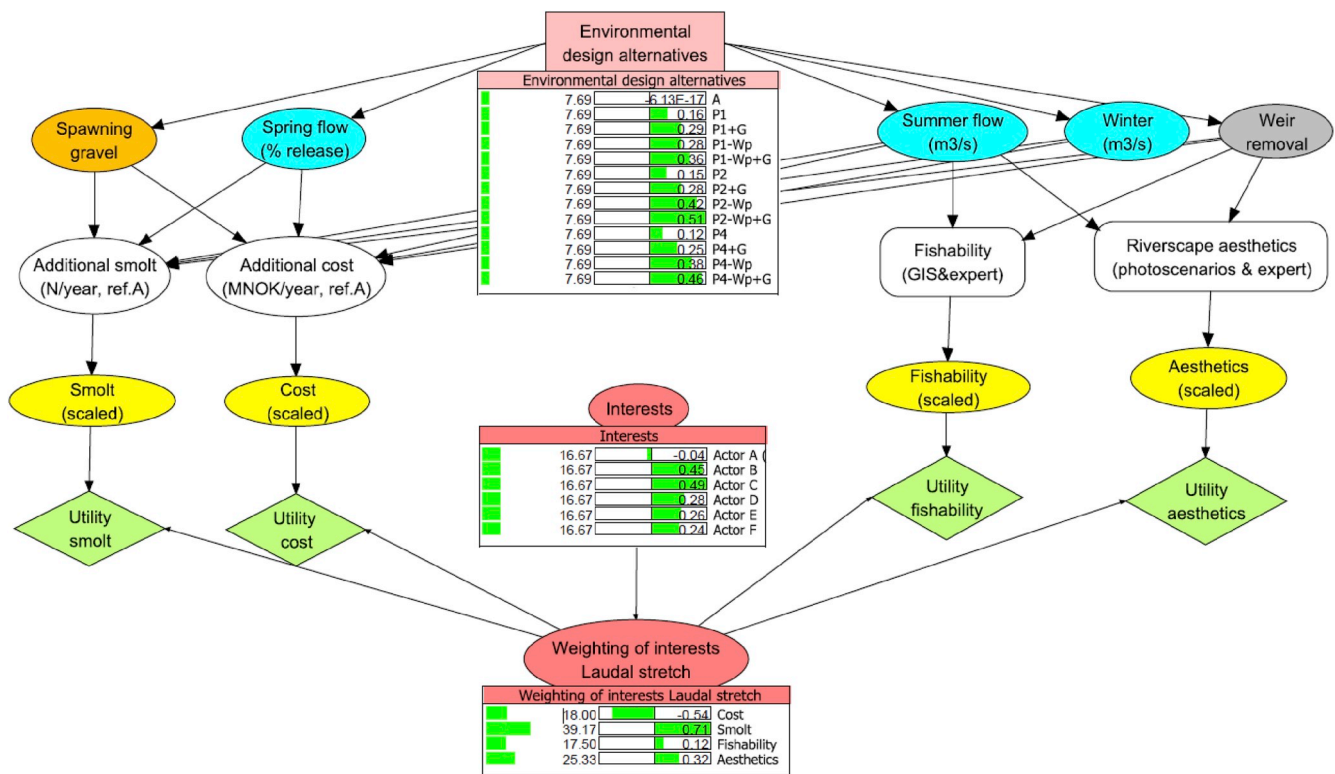


Fig. 6. Default MCDA model without evidence. Object oriented Bayesian network for MCDA of environmental design alternatives in the Laidal bypass, Mandalselva.

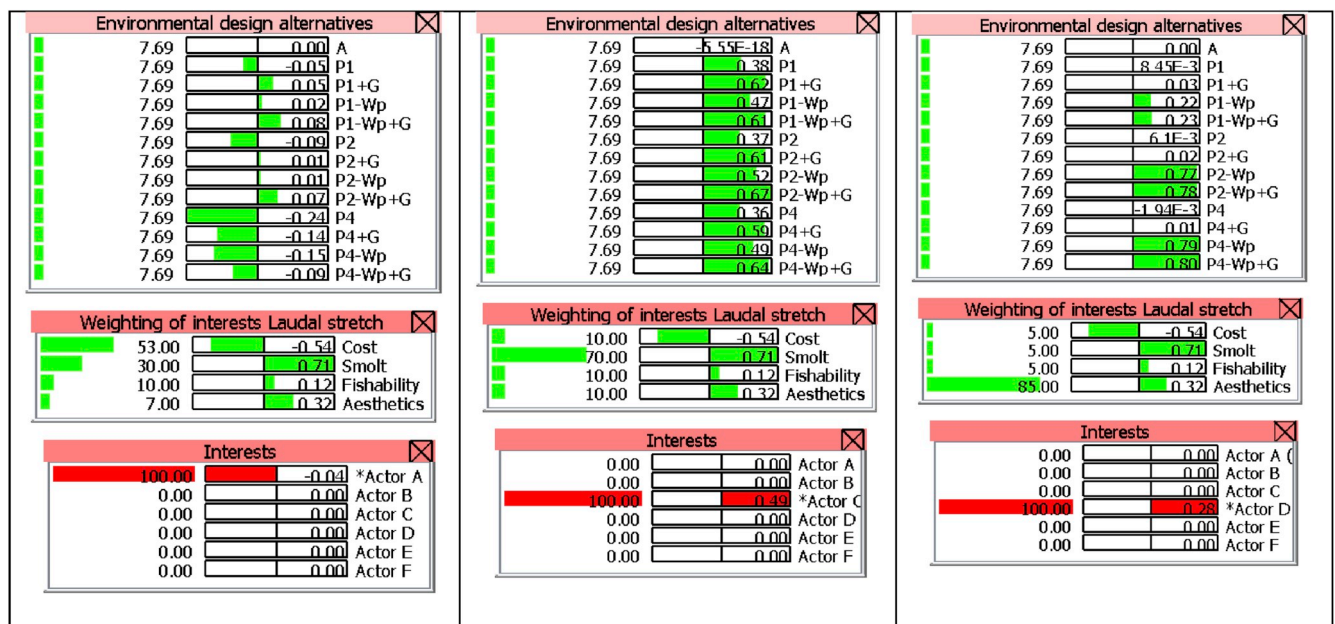


Fig. 7. Actor interest perspective on MCDA. Utility of 3 main environmental design alternatives P1, P2 and P4 conditional on the criteria weights of actors A, C and D (examples). Probabilities are shown to the right, and expected utilities to the left in each panel.

(-0.04) if no further evidence is available on design alternatives. Looking more closely at the design alternatives (upper left hand panel), P4 scenarios have unequivocally negative utility; both P1 and P2 are positive if habitat remediation measures are included, with a slight preference for P1 scenarios. Costs have the highest weight for Actor A (P (cost) = 53%; P(smolt) = 30%; P(fishability) = 10%; P(aesthetics) = 7%). For Actor C all alternatives are positive with a preference for P2-

Wp + G (E(utility) = 0.67); preferences are dominated by P(smolt) = 70%. Actor D has a preference for P4-Wp + G, with weir removal alternatives influencing choices heavily; preferences are dominated by P (aesthetics) = 85%.

Fig. 8 shows an impact criteria weighting perspective on the MCDA, demonstrating another form of diagnostic reasoning using BN in inference mode. What alternatives are preferred when an 'extreme positions'

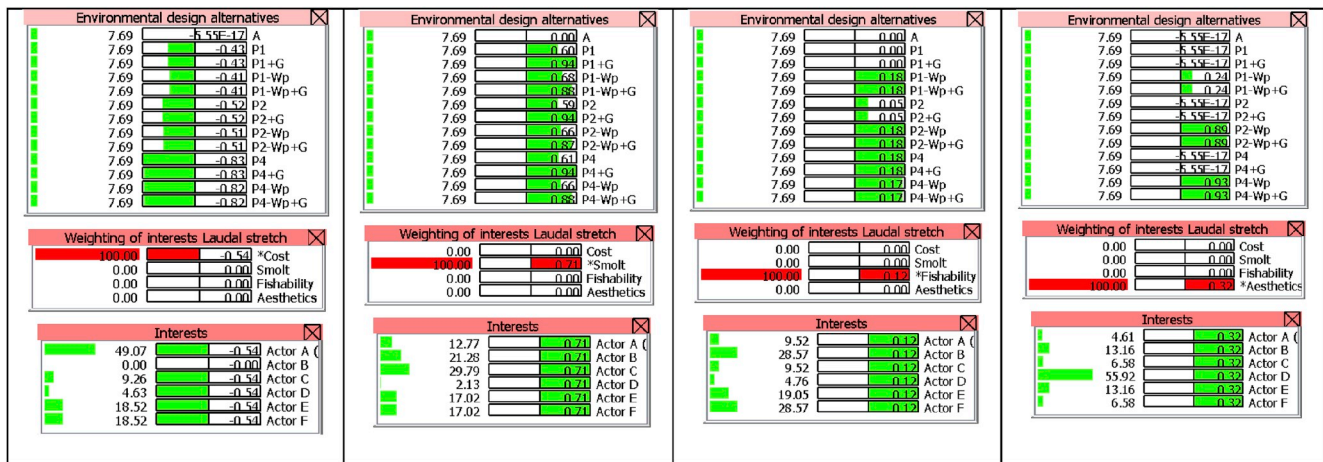


Fig. 8. Impact criteria weighting perspective on MCDA. Utility of design alternatives in relation to specific criteria. Probabilities are shown to the right, and expected utilities to the left in each panel.

is taken with all preference weight given to a specific criteria? The network infers the utility of each environmental design scenario when a specific criteria is allocated 100% importance (middle panel).

The relative importance of the selected criteria for each actor is shown in the lower panel. For example, if costs are the only decision criteria, P1 scenarios have the lowest foregone hydropower production - hence the lowest negative utility - and are preferred. Cost has greatest relative importance for Actor A (49%). Scenarios with more flow, weir removal and spawning gravel are preferred if smolt is the only decision criterion - notably spawning gravel has a relatively large impact on utility. For the fishability criteria, once weirs are removed changes in flow have little impact on utility. This is because of the low variability in salmon habitat extent for the flow ranges of a restored riverbed. Finally, riverscape aesthetics require a combination of weir removal combined with greater flow. Weir removal more than doubles utility if flow is increased from 3 m³/s (P1) to 6 m³/s (P2).

4. Discussion

4.1. Implications for environmental design decisions in the Mandalselva River

As in [Bustos et al. \(2017\)](#) we find that habitat remediation measures have a larger impact on utility than changes in environmental flow. Did our addition of fishability and aesthetics impacts modify conclusions about preferred flow scenarios? Weir removal had a large positive impact on fishability, but assuming weir removal is in place, increases in flow had small or no net effects across different mesohabitats that are attractive for fishing. Weir removal had a relatively small impact on aesthetic value of the riverscape which was reinforced by increased eflow. We note that these considerations are the result of scaling of impacts by an expert panel, while stakeholders provided the relative weighting of the importance of each impact. Different decision alternatives could have been possible if stakeholders had also been asked to evaluate the scaling of fishability and aesthetics.

4.2. Potential improvements in sub-models

The results of the MCDA are sensitive to assumptions in the sub-models. A more detailed discussion of potential sub-model improvements can be found in [Supplementary Materials](#). Here we summarise the challenges of identifying uncertainty in the submodels. Assessment of impact criteria in MCDA often assumes that criteria are independent, while this is often not the case in environmental management ([Beinat, 1997](#)). In our case, several interdependencies are modelled outside the

OoBN ([Fig. 1](#)) and as such are not represented explicitly in the Bayesian network ([Fig. 3](#)).

- Change in wetted area assessed using the hydraulic model determines the availability of salmon habitat simulated in the salmon population model, mesohabitat mapping and photo-scenarios
- Water velocity and depth determine mesohabitat quality for fishing. Water velocity was used by experts to adjust illustrations in the photo-scenarios.
- IB-salmon was simulated for changes in wetted area, but water velocity and depth do not determine smolt productivity directly (size of wetted area is a proxy for combined effect of flow and depth).

Bayesian networks are ideal for specifying the conditional probabilities due to ecosystem functional relationships between impacts. We could not make full use of this feature in this study due to limitations in jointly simulating sub-models. In the MCDA appraisal process, management options under investigation should ideally be iteratively updated by repeated model simulation. For this to be possible simulation models need to have faster run times to allow for updating of management assumptions. In our case, the hydraulic modelling of wetted area and IB-salmon is the 'keystone' in the model chain. At present the capabilities of IB-salmon for uncertainty analysis are limited to sensitivity analysis due to long run times of dynamic individual-based population simulation models. This limited the combinations of environmental flow and habitat restoration measures that we could simulate and emulate in a sub-network within a OoBN. In future applications Hugin's machine learning functionality could be used emulate the computationally demanding dynamic models. Improvements would include Monte Carlo Markov Chain capabilities in IB-salmon and hydraulic models, combined with greater computing power. Furthermore, linked simulation is important in capturing the covariation across impacts - power loss and smolt production - without which joint uncertainty across all impacts may be overestimated ([Barton et al., 2016a](#)). Better modelling of covariance for qualitative assessments such as river aesthetics and mesohabitat fishability could also be achieved with more resources in future applications. In our simple example, we only modelled these impacts for summer conditions, assuming no impacts in winter or spring.

4.3. Uncertainty analysis in MCDA using OoBNs

Our MCDA application in OoBN demonstrates how Bayesian inference can be used for rapid sensitivity analysis from different perspectives - providing evidence to different nodes in the network. The OoBN HUGIN computes and displays marginal utilities of all states in the

model. Marginal utilities can be interpreted directly as the relative influence of any particular node state on the utility of alternative decisions. The deployment of the model online makes experimentation with different conditioning factors accessible without technical expertise (Madsen et al., 2013).

While more participatory appraisal of uncertainty in MCDA is facilitated by a Bayesian network approach, the explicit quantification of uncertainty imposes additional assumptions of its own. Simulation results from hydropower production have high temporal resolution. We discretized the daily cost simulation output into a limited number of intervals representing annual totals, which leads to some information loss (Uusitalo, 2007). This is an example of an information cost of MCDA integrating across precise quantitative and less precise qualitative impacts. Structural robustness analysis can be carried out by implementing Bayesian network with nodes with high/low resolution in discretization of continuous variables. Nodes with more states increase the complexity of a network exponentially (Marcot et al., 2006). Value of information (VoI) analysis can be used to compare how much entropy is reduced in a specified decision node, from obtaining additional evidence in different nodes in a Bayesian network (Hugin, 2014). Unfortunately, VoI comparing variables in all submodels in an OOBN is not possible to carry out in Hugin software – only the variables in the main model are assessed. For VoI to cover all variables a non-hierarchical model could be specified. This could have been manageable in our simple network. However, in MCDA with more criteria, and with sub-models with many nodes, this can result in a complex network structure which does not communicate the model purpose very well. These are all examples of increasing information costs with increasing diverse and plural valuation (Barton et al., 2017).

4.4. Valuation biases in MCDA

In many circumstances, allowing experts to provide uncertainty judgements and avoiding forcing precise estimates from them is fundamental to a fair and trustworthy representation of value functions. However, it complicates the computational requirements of the model (Beinat, 1997). In this paper we show that conditional probability tables in Bayesian networks provide an easy implementation of the approach to value function uncertainty in MCDA advocated by Beinat (1997). The approach splits preference elicitation into (i) scaling of value functions and (ii) direct weight rating. While it allows impacts to be compared using multi-attribute utility functions, it splits the preference system in two parts and is prone to error accumulation (Beinat, 1997). For the convenience of demonstrating MCDA using Bayesian networks, we assigned the role of value scaling to experts. It could have been carried out by stakeholders or users in a more participatory implementation. For example, the hydropower company's willingness to forego power production could have been implemented as a non-linear scaling function with a threshold for some level of cost considered disproportionate. Similarly, specific user groups could have been asked to assess and scale fishability (fishers) and aesthetics (visitors and residents) (Aas and Onstad, 2013).

Consistent weighting of impacts depends on stakeholders being familiar with the full range of each impact for the best and worst alternatives. Weighting is jointly determined with value scaling (Beinat, 1997). Stakeholders involved were member of the Environmental Design project reference group, and generally familiar with alternatives under consideration. They had little difficulty in providing quantitative weights through a questionnaire, and in comparing their weights to guesses about other stakeholders' weights. However, the range of impacts was not presented to them in the questionnaire itself, and we do not know whether availability of this additional information would have changed their relative weights. These limitations could have been addressed by a different participatory process in our study, and we believe could be easily accommodated by an object-oriented modelling approach to MCDA.

4.5. Stakeholder assessment MCDA

During the final year of our study (2016) the hydropower operator Agder Energy removed all weirs and conducted other habitat remediation measures in the Laudal stretch. The MCDA and stakeholder preference survey were conducted prior to removal of the weirs in 2015–2016. Final discussions with stakeholders regarding the relevance of the MCDA was conducted after weir removal January 2017. Stakeholder assessed advantages and disadvantages of multi-criteria decision analysis as support for environmental design in the Mandalselva. Stakeholders found Bayesian networks to be a transparent and systematic documentation of multiple impacts and differences between their interests. However, stakeholders also found the MCDA challenging because of their unfamiliarity with the two new criteria we introduced in our study - quantitative impact assessments of fishability and aesthetics. Some stakeholders found the choice of 'mesohabitat' quality as an excessively narrow proxy for fishability. Although the stated purpose of the MCDA was to evaluate alternatives across initially incommensurable impact indicators, some stakeholders found the analysis to be incomplete in not having valued all ecosystem services monetarily. Some stakeholders admitted that their preferences expressed in terms of weights were tentative due to their lacking a formal mandate and/or a formal hearing process not being integrated in the study. Finally, stakeholders were surprised at what they considered to be a low sensitivity of decision alternative rankings to changes in preference weights.

Further discussion of the stakeholder evaluation can be found in [Supplementary Material S8](#). The limitations they point out are in part due to the focus of the research in demonstrating MCDA implementation in a Bayesian network, rather than a contracted decision-support consultancy. We think that MCDA modelled in Bayesian networks could go some way to formalizing preference uncertainty and stakeholder representativity using conditional probability distributions. In the current model, impact criteria weights are represented as conditional probability distributions, while each stakeholder's preferences have equal weight. A utility function could also be defined in which stakeholders' preferences are assigned probabilities depending on how representative they are in the affected population.

The insensitivity of outcomes to stakeholder preferences may in part be a feature of BNs' modelling of impacts of different river regulation alternatives as probability distributions. Our analysis shows that the more uncertain modelled environmental impacts are, the less the ranking of alternatives is sensitive to stakeholder preference assessment (under reasonable assumptions about preferences, such as excluding lexicographic preferences assigning 100% weight to a particular criterion). While this initially looks like a barrier to applying MCDA, the OOBN helps us to formulate critical questions about the value of information in collecting (i) stakeholders' preferences, versus spending limited research resources on improving (ii) the accuracy of impact assessments, or (iii) conducting pilot projects and experiments, to reduce uncertainty. Effectively, a Bayesian network helps researchers ask diagnostic questions of an MCDA regarding the value of information across different types of environmental appraisal activities, including stakeholder preference assessment.

5. Conclusions

The main aim of our paper was to demonstrate the use of Bayesian networks in MCDA for environmental management. We demonstrate how MCDA using multi-attribute value functions could be implemented in an object-oriented Bayesian network with decision and utility nodes. We show how the OOBN can be used to integrate quantitative model simulation with qualitative expert judgement models of impacts. We integrated available models and data (hydropower and smolt production) and created new expert-based models (fishability and aesthetics). The way each of the submodels deals with uncertainty in parameters and causal factors is different and at first glance 'inconsistent'. However, this

is the ‘messy’ reality of integrating available knowledge in decision support. The strength of the Object-oriented modelling approach is that different sub-models with their assumptions can be integrated in a single MCDA, using Bayesian networks to diagnose their impacts on decision options.

The paper also demonstrates how conditional probability tables used in Bayesian networks are useful for modelling uncertainty in value scaling functions and for formalizing the variation in criteria weight rating due to the diversity of stakeholder preferences. To our knowledge this is the first example of MCDA in Norway integrating assessment of eflow and morphological restoration measures in regulated rivers. Our impact assessment spans the provisioning ecosystem services of hydro-power production; cultural ecosystem services of recreational salmon fishing and riparian landscape aesthetics; and the supporting services of habitat quality for salmon smolt. It is also the first environmental application of MCDA using a Bayesian network approach that we know of in the literature.

The study also provided practical recommendations on environmental design and hydro-power regulation of the Laudal stretch of the Mandalselva River in Norway. Our analysis reinforces and elaborates on an earlier cost-effectiveness assessment by Bustos et al. (2017) which pointed out that morphological river restoration measures can compensate for lower eflows. Our analysis extends the scope of this previous study with an assessment of fishability and riverscape aesthetics. We find that eflows have a smaller effect on fishability and aesthetics than if they are combined with physical weir removal. The study provides further support for the argument that physical river restoration can reduce eflow requirements and thereby reduce the loss in hydropower production, while at the same time gaining satisfactory conditions for angling and landscape aesthetic interests.

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Software and/or data availability

Software: <https://www.hugin.com/>
Online model: http://demo.hugin.com/example/MCDA_OOBN.
MethodsX paper with Supplementary Material: <https://doi.org/10.1016/j.envsoft.2019.104604>.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envsoft.2019.104604>.

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